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The effect of residual gas concentration and engine speed on the detonation characteristics of iso-octane, triptane, di-isobutylene, and ethyl benzene

Sorensen, Robert Ernest; Graffy, Richard; Richards, J.M.; Cullin, W.H.

Massachusetts Institute of Technology

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THE EFFECT OF RESIDUAL GAS CONCENTRATION  
AND ENGINE SPEED ON THE DETONATION  
CHARACTERISTICS OF ISO-OCTANE,  
DI-ISO-BUTYLENE, TRIPTANE  
AND ETHYL BENZENE

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THE EFFECT OF RESIDUAL GAS CONCENTRATION AND ENGINE SPEED  
ON THE DETONATION CHARACTERISTICS OF  
ISO-OCTANE, DI-ISO-BUTYLENE, TRIPTANE AND ETHYL BENZENE

by

Robert E. Sorensen, Lt. Comdr. USN

William H. Cullin, Lt. Comdr. USN

John M. Richards, Lt. Comdr. USNR

Richard Graffy, Lieut. USN

Submitted in Partial Fulfillment of the Requirements for  
the Master of Science Degree in Aeronautical Engineering

from the

Massachusetts Institute of Technology

1947



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FOR THE YEAR 1903

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UNIVERSITY OF CALIFORNIA  
AT BERKELEY

Cambridge, Massachusetts  
23 May 1947

Professor Joseph S. Newell  
Secretary of the Faculty  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

Dear Professor Newell:

A thesis entitled "The Effect of Residual Gas Concentration and Engine Speed on the Detonation Characteristics of Iso-Octane, Di-iso-butylene, Triptane and Ethyl Benzene" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Respectuflly yours,

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### ACKNOWLEDGMENT

The investigation reported in this thesis was conducted in the Sloan Automotive Laboratory, Massachusetts Institute of Technology, over the period October 1, 1946 to May 24, 1947.

The authors desire to acknowledge their appreciation of the help rendered them by the following people:

Professor W. A. Leary, M.I.T. Staff  
Research Assistant J. C. Livengood, M.I.T. Staff  
Instructor C. H. Kano, M.I.T. Staff  
and  
the mechanics and assistants of the Sloan Laboratory.

## Summary

The investigation reported in this report was conducted in the field and laboratory, and the results are presented in the following sections. The investigation was conducted from October 1, 1944 to May 31, 1945. The results of the investigation are presented in the following sections: 1. Description of the field work. 2. Description of the laboratory work. 3. Results of the field work. 4. Results of the laboratory work. 5. Conclusions.

## Field work

Professor E. A. Smith, D. Sc., and  
Assistant E. A. Smith, D. Sc., and  
Assistant E. A. Smith, D. Sc., and  
and  
the results and conclusions of the field work.



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1. The first step in the process of the  
 2. is to determine the scope of the  
 3. project. This involves identifying the  
 4. objectives and the resources available.  
 5. The next step is to develop a plan of  
 6. action. This plan should outline the  
 7. steps to be taken and the responsibilities  
 8. of the individuals involved. It should  
 9. also include a timeline for the project.  
 10. Once the plan is developed, the next  
 11. step is to implement it. This involves  
 12. carrying out the tasks outlined in the  
 13. plan. It is important to monitor the  
 14. progress of the project and to make  
 15. adjustments as necessary.

1944-1945

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9	Appendix C: Interview transcripts
10	Appendix D: Survey results
11	Appendix E: Final report

## INTRODUCTION

The purpose of this paper is to study the effect of residual gas concentration on the critical pressure-time characteristics of (1) Iso-Octane, (2) Di-iso-butylene, (3) Triptane, and (4) Ethyl Benzene.

It has been observed by experimenters in the General Motors Laboratory, Sloan Laboratory, and elsewhere, that the critical pressure of Iso-Octane increases with increase in RPM while the critical pressures of Ethyl Benzene, Triptane, and Di-iso-butylene decrease with increase in RPM. The simple auto ignition theory does not account for this behavior since it states that the critical pressure should increase with increase in RPM regardless of the fuel, provided other variables are held constant.

A further study of the subject by Leary and Taylor (Reference 1) showed that the effect of engine speed on critical pressure is due to "time effect" alone. The expression "time effect" is defined as

- (1) the rate at which the end gas is compressed and
- (2) the time required by the end gas to complete the necessary preliminaries to explosion.

The term "critical pressure" is defined as

- (1) that pressure at which the end gas explodes to cause the phenomenon known as detonation.

# INTRODUCTION

The purpose of this paper is to study the effect of  
various factors on the critical pressure-  
temperature of (1) low-temperature, (2) intermediate,  
(3) high-temperature, and (4) supercritical.

It has been observed by experimenters in the past  
that pressure, temperature, and composition, and  
the critical pressure of low-temperature systems with increasing  
in the while the critical pressure of high-temperature systems,  
and of intermediate systems with increasing in the. The simple  
and liquid theory does not account for this behavior since  
it states that the critical pressure should increase with in-  
crease in the temperature of the fluid, whereas other variables  
are held constant.

A further study of the subject by many other  
investigators (1) showed that the effect of various gases on critical  
pressure is due to "the effect" alone. The experimental "line  
effect" is defined as

- (1) the rate at which the gas is compressed and
- (2) the time required for the gas to complete the  
necessary preliminary to reaction.

The term "critical pressure" is defined as  
(1) that pressure at which the gas begins to  
undergo the transition from a liquid to a gas.

It is suspected that the residual gas concentration in the end gas may influence the "time effect" in such a way as to cause an increase in critical pressure with increased RPM using Iso-Octane, and a decrease in critical pressure with increased RPM using Ethyl Benzene, Triptane, and Di-iso-butylene.



It is suggested that the National War Commission be  
the one to receive the "war effort" in such a way as  
to make the National War Commission in charge of the  
war effort, and a National War Commission be  
created to receive the "war effort" in such a way as

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## SUMMARY

It was found that the critical pressure of Triptane, Ethyl Benzene and Di-iso-butylene was higher at 900 RPM than at 1800 RPM at all values of residual gas concentration whereas the critical pressure of Iso-octane was higher at 1800 RPM than at 900 RPM for all values of residual gas concentration. Thus the residual gas concentration and its influence on time effects is not the cause of the difference in behavior of the detonation-RPM characteristics of Iso-octane from those of Triptane, Di-iso-butylene and Ethyl Benzene.

It was also found that at both RPM's an increase in residual gas concentration caused an increase in critical pressure for all fuels.



## FUELS

The tests to be described were carried out on Iso-Octane, Di-iso-butylene (SR 10), Triptane and Ethyl Benzene. About twenty gallons of each of these fuels were required to complete the tests.

The Iso-Octane (2-2-4 trimethyl pentane) was obtained from Stanco Distributors, Inc. in five gallon drums. The calculated chemically correct fuel-air ratio was .0665.

The Di-iso-butylene was obtained from Stanco Distributors, Inc. under the designation SR 10 in five gallon drums. The calculated chemically correct fuel-air ratio was .0681.

The Triptane was obtained from N.A.C.A., Cleveland, Ohio, via the Bureau of Aeronautics, Navy Department. The chemically correct fuel-air ratio was .0662.

The Ethyl Benzene was obtained from the Dow Chemical Co. The chemically correct fuel-air ratio was .0736. Some difficulty was experienced in handling Ethyl Benzene because of its tendency to attack rubber and plastic and its nauceous odor.





## DESCRIPTION OF APPARATUS

A standard C.F.R. single cylinder, water cooled, variable compression ratio engine 3.25 inch bore and 4.5 inch stroke having no valve overlap was used. (See Appendix B)

The air induction system consisted of an aluminum oxide drying tower (Reference 4) to keep the air humidity as low and as constant as possible, a surge tank, and a vaporizing tank, the temperature of which was controlled by any desired combination of steam and cold water. An immersion type electric heater, 220 volts, 4000 watts, was used to supplement the vaporizing tank when high inlet temperatures were used. The air supply came from a 100 lb/in.<sup>2</sup> high pressure line and then came through high and low pressure regulator valves. After passing through the drying tower, the air was metered through a .515 inch A.S.M.E. orifice and the pressure differential across the orifice was measured with a standard water manometer.

The fuels were metered through a calibrated rotameter, Fisher and Porter, No. 1A-25, to a Bosch controllable flow injection pump which allowed any desired fuel rate to be set and held constant. The fuels were gravity fed with a head of approximately eight feet.

The exhaust system led through a surge tank in which cold water was sprayed for cooling purposes. The exhaust pressure

The air compressor system consisted of an electric motor driving a compressor (Fig. 1) to supply the air directly to the tank, and a constant pressure, a large tank, and a regulating valve, the pressure of which was controlled by air passing through a 1/2 inch I.D. valve and the pressure differential across the valve was measured with a standard water manometer.

The tank was entered through a calibrated manometer, 1/2 inch I.D., to a tank containing the injection pump which allowed the desired flow rate to be set and maintained. The tank was fitted with a head of approximately 100 ft.

The exhaust system led through a pipe that in which case water was required for cooling purposes. The exhaust pressure



was controlled by means of a throttling valve and exhaust pump. A mercury manometer was used for measurement of normal exhaust pressure and a standard Bourdon tube gage was used for measuring high exhaust pressure.

Engine coolant temperature was held constant by allowing the jacket water to boil. Uniform cooling was aided by an externally driven centrifugal pump and excessive loss of water was prevented by a condenser coil at the top of the jacket.

The engine was connected to a D.C. dynamometer which was used as a motor for starting and as a generator for absorbing the power output of the engine when firing. To maintain the RPM at 900, two 60 ampere, 220 volt resistance stoves were used in the armature circuit. When operating at 1800 RPM, the armature discharged into the main line. The RPM could be accurately controlled by varying the dynamometer field strength and was measured by a tachometer and a strobotac operating on a 60 cycle frequency.

The ignition system operated from 110 volt D. C. line. The spark advance was controlled by a breaker mechanism coupled directly to the crankshaft. A Champion RJ-2 spark plug was used for Iso-Octane, Di-iso-butylene and Triptane. A Champion C-7 spark plug was used for Ethyl Benzene because of its tendency to foul the spark plug at low RPM.

Engine oil temperature was controlled by the proper regulation of steam or cold water in the oil heat exchanger.



Incipient detonation was determined by a Dumont Oscillograph, type 168, using a M.I.T. magnetic pick-up whose output is proportional to  $dp/dt$ . (Reference 3)

The engine indicator cards were taken on a M.I.T. high-speed engine indicator card machine using pressure balance springs giving 10, 20, 150 and 200 lbs. of pressure per inch of ordinate along with a M.I.T. balanced diaphragm pick-up unit. (Reference 2)



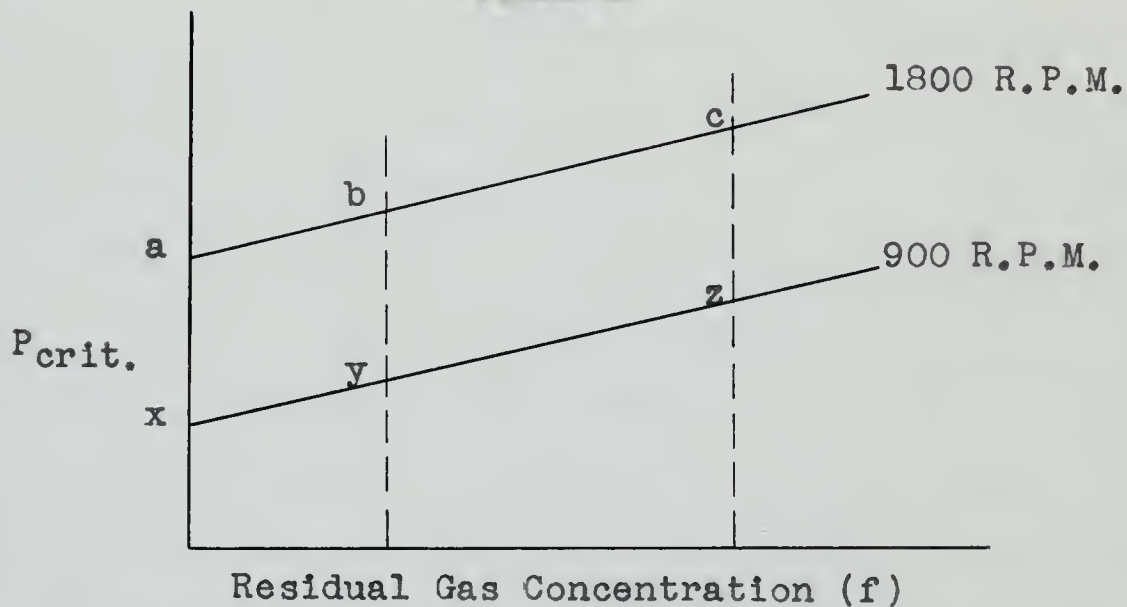


## PROCEDURE

Before a discussion of the actual experimental procedure can be attempted, it is necessary to look into the theory involved in order to justify some of the steps taken.

If the critical pressure is plotted against residual gas concentration ( $f$ ), and the function is assumed to be linear, the result is a plot as shown in Figure A. The line a-b-c will then show the variation of critical pressure with residual gas concentration at 1800 RPM, and the line x-y-z will show the variation at 900 RPM. The fuel is assumed to be one which acts like iso-octane giving higher critical pressures at higher RPM's.

FIGURE A



Furthermore, it should be noted that at any point (z) on the 900 RPM line the same concentration of residual gas is in contact with the end gas for a longer time than at the



# Experiment

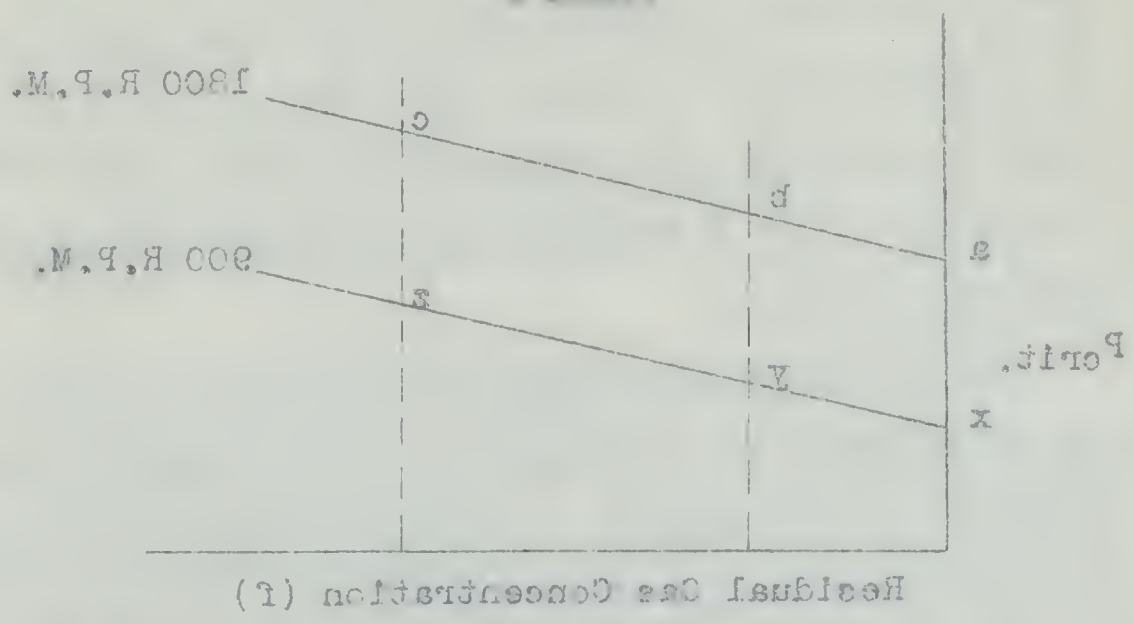
Before a discussion of the actual experimental procedure can be attempted, it is necessary to know that the theory involved in this experiment is that of the effect of temperature on the rate of reaction.

It has already been shown in previous experiments that the rate of reaction is affected by temperature. In this experiment, the rate of reaction is measured at two different temperatures, 100°C and 120°C, and the time taken for a certain amount of reaction to take place is recorded. The results are shown in the following table:

Temperature (°C)	Time taken (sec)
100	1800
120	900

From these results, it can be seen that the rate of reaction is doubled when the temperature is raised from 100°C to 120°C.

Figure 1



Furthermore, it should be noted that the rate of reaction is also affected by the concentration of the reactants. In this experiment, the concentration of the reactants is kept constant, and the effect of temperature is studied.

corresponding point (c) on the 1800 RPM line, the time of contact being inversely proportional to the RPM.

In order to compare the effect of residual gas concentration on the end gas at different RPM, a satisfactory basis of comparison had to be decided upon. If compression is assumed to be isentropic and two initial cylinder charges are chosen with identical fuel-air ratio, residual gas concentration, and initial entropy, both charges will follow the same compression path as plotted on a Pressure-Volume diagram or Temperature-Entropy diagram even though one charge is compressed at 900 RPM and the other at 1800 RPM.

By taking four such charges with identical initial entropy, two of which have a low residual gas concentration and two having a high residual gas concentration, the critical pressures may be measured and a plot may be constructed similar to Figure A. The absolute slopes of these plotted lines may then be explained on the basis of

- (1) the residual gas concentration in the end gas, and
- (2) the length of time in which the residual gas is in contact with the end gas.

In performing this experiment, two cylinder charges were chosen with the same initial entropy but with different residual gas concentration and the necessary data was obtained at 900 RPM to plot a line similar to x-y-z in Figure A. This was repeated at 1800 RPM attempting to maintain the same initial entropy and thereby plot a line similar to a-b-c. The actual experimental methods used are described below.

transmission path (1) on the 1000 Hz line, the time of

transmission is approximately 100 ns.

It is also possible to observe the effect of various

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It is also possible to observe the effect of various

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## EXPERIMENTAL PROCEDURE

Prior to firing, the engine was motored for several minutes by means of the dynamometer. Since the drying tower had to be reactivated after fourteen hours of use, atmospheric air was used during this and all other times that actual runs were not being made. At this time the top-dead-center line on the high speed indicator machine was checked and necessary adjustments were made if needed. The barometer was also read and calculated to an accuracy of one-hundredth of an inch of mercury. An approximate fuel-air ratio was set and when the temperature in the mixing tank reached a point where complete vaporization was assured, the ignition was turned on and the engine allowed to fire. After a warm-up period of about one hour, the RPM was adjusted to that desired.

In order to have a logical basis of comparison between runs made with the same fuel and same RPM but with different residual gas content, it was necessary to make some one point on the compression stroke of each of the two runs identical in cylinder pressure and specific volume, and consequently the same entropy. This point was arbitrarily taken at  $110^\circ$  of crank angle before top-dead-center as measured on the indicator card of the high-speed indicator machine. This point was chosen as close to the beginning of the compression stroke as possible consistent with good accuracy of pressure measurement on the indicator card.

There is no doubt that the results of this

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There are a number of other factors that may be involved in the development of the disease.

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It was decided to vary the residual gas content by means of the exhaust pressure. The two values of exhaust pressure used were 45 psia and 14.7 psia for high and low residual gas content respectively, with the exception of Ethyl Benzene. These pressures were obtained by means of a throttling valve placed in the pipe between the exhaust tank and the laboratory exhausting pump.

Since the high exhaust pressure was difficult to control, the first of each series of two runs was made with an exhaust pressure of 45 psia. The inlet temperature was held constant at a low value but high enough to give complete vaporization of fuel in the mixing tank. Inlet pressure was adjusted to give incipient detonation at a reasonable compression ratio.

With the RPM, exhaust pressure, inlet temperature and inlet pressure held constant, the air flow rate was measured and the corresponding fuel-air ratio was set by means of the rotameter and controllable flow fuel pump. The compression ratio giving incipient detonation was then obtained. Air flow rate was again measured, and, if a small deviation was noticed, the fuel rate was changed to keep a constant fuel-air ratio. The compression ratio was again checked, and, if a change was necessary, it was always so slight that no measurable difference was noticed in any of the other variables.

At this point all operating conditions were held constant, and pressure versus crank angle diagrams were made by means of





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the M.I.T. high-speed indicator card machine. These cards were used in the determination of residual gas content, critical pressure, and for maintaining similar cylinder conditions at  $110^{\circ}$  before top center for comparable runs. Depending upon the type of fuel used, with their accompanying cylinder pressures, cards were taken using springs giving either 10 lb/in. or 20 lb/in. ordinate for high accuracy at low pressures; and either a 150 lb/in. or 200 lb/in. ordinate spring was used for determining the critical pressure obtained in the cycle.

The cylinder pressure occurring at a point  $110^{\circ}$  B.T.C. was measured from either the 10 lb or 20 lb card, and the specific volume of the cylinder gases at this point was computed by the equivalent cycle method. (See Appendix A)

For the second run of the series using the same fuel and engine RPM but with 14.7 psia exhaust pressure and consequent lower residual gas content, it was necessary to duplicate this cylinder pressure and specific volume at  $110^{\circ}$  B.T.C.

To accomplish this, a new card was inserted in the indicator machine on which this same pressure was marked at  $110^{\circ}$  B.T.C. The inlet temperature was raised and the inlet pressure was adjusted until the compression line on the second run ran through the marked pressure point. With the pressure thus fixed, the remaining variable was the specific volume. This was computed by the same equivalent cycle method and, if





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in disagreement with the volume found for the first run, the inlet temperature was lowered or raised to decrease or increase the specific volume. At the same time, the inlet pressure was readjusted to keep the compression line going through the marked point. After several trials, a combination of inlet temperature and inlet pressure was found to give the same pressure and volume in the cylinder at 110° B.T.C. as in the first run.

When this combination had been found, all variables were held constant and cards were again taken on the high-speed indicator machine.

This procedure was used for each fuel in an attempt to obtain identical compression entropies at 900 and 1800 RPM's. (See Precision of Results)

With Ethyl Benzene it was necessary to use an inlet temperature of 150° F instead of 120° F to insure complete vaporization of the fuel in the mixing tank. As a consequence, the volume for the high exhaust pressure run was so high that it could not be duplicated in the low pressure run by raising inlet temperature alone. Thus it was necessary to increase the exhaust pressure above the 14.7 psia value to raise the volume at 110° B.T.C. to the necessary value.





## RESULTS

The results of this experiment are contained in Table I and Figures 5 and 6.

In all the fuels tested, the critical pressure increased with an increase in residual gas concentration, thus giving a positive slope to all plots of critical pressure versus residual gas concentration, regardless of RPM.

However, the difference in slope of the 1800 RPM line relative to the 900 RPM line for each fuel is caused by the change in the time of contact of the residual gas with the end gas. These differences in slope were found to be as follows:

Iso-Octane: The slope of the 900 RPM line is greater than that of the 1800 RPM line.

Ethyl Benzene: The slope of 900 RPM line is greater than that of the 1800 RPM line.

Triptane: The slope of the 1800 RPM line is greater than that of the 900 RPM line.

Di-iso-butylene: The slope of the 1800 RPM line is greater than that of the 900 RPM line.

With Iso-Octane a higher critical pressure was obtained with 1800 RPM regardless of residual gas concentration. However, Ethyl Benzene, Triptane and Di-iso-butylene gave higher critical pressures using 900 RPM for all values of residual gas concentration.



The results of this investigation are presented in Table

I and figures 1 and 2.

In all the cases, the critical pressure increased with the increase in the initial pressure. This shows a positive effect of the initial pressure on the critical pressure. The critical pressure, however, is also a function of the initial pressure.

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It is seen from the figures that the critical pressure is a function of the initial pressure.

The pressure versus time curve (Fig. 6) shows that the rate of compression for 1800 RPM is greater than that for 900 RPM at all comparable points on the compression path.

and the following conditions are satisfied:

*(continued from page 6)*

## DISCUSSION OF RESULTS

The results of this experiment (Fig. 5) show that there is a difference in the relative slopes of the 900 RPM and 1800 RPM lines for a given fuel.

Iso-Octane and Ethyl Benzene show the 900 RPM line as having a greater slope than the 1800 RPM line. This indicates that a shorter time of contact between the residual gas and the end gas allows the end gas to detonate more easily.

Di-iso-butylene and Triptane show the 1800 RPM line as having a greater slope than the 900 RPM line, giving opposite results to those obtained for Iso-Octane and Ethyl Benzene. That is, a shorter time of contact between the residual gas and the end gas allows the end gas to detonate less easily. The effects as evidenced by the slight differences in slope are quite small.

In an attempt to explain the above effects, it is assumed that residual gas in some way catalyzes or inhibits the preliminaries to detonation in the end gas. That is, if the chemical preliminaries to detonation were inhibited by the residual gas, as in the case of Iso-Octane and Ethyl Benzene, and if the preliminaries to detonation were catalyzed by residual gas as in the case of Di-iso-butylene and Triptane, then the observed effects are explained.

It must be pointed out that this discussion applies only



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to the relative slopes of the 900 RPM and 1800 RPM lines for any given fuel and consequently deals only with the effect of residual gas concentration on the pressure-time characteristics of the fuels studied.

The results also show that all fuels at all RPM's have positive increases in critical pressure with an increase in residual gas concentration. This increase can be explained by the fact that the residual gas dilutes the end gas and may, therefore, inhibit the processes necessary to bring the end gas to explosion. This effect may be purely a physical one, i. e., keeping the reacting molecules of the end gas apart physically, thus reducing the rate at which chain reaction proceeds. The dilution effect is influenced by the participation of the residual gas components in the chemical preliminaries to detonation as discussed in the preceding paragraphs.

The rate of compression of the residual-end gas combination was higher at 1800 RPM than at 900 RPM, but under the experimental conditions used, there was no way of maintaining a constant rate of compression for all fuels at the same RPM. Hence, no comparative discussion can be made on the effect of rate of compression.





## PRECISION OF RESULTS

### DETONATION

The error involved in judging the detonation level of a given fuel under different operating conditions were almost entirely personal since the critical compression ratios were judged entirely by observation of the oscillograph pattern. A single operator was charged with the estimation of incipient detonation. The variation in compression ratio for several runs is given below for Triptane.

Run Number	Trial Number	Micrometer Reading	Compression Ratio	Error in Estimated C.R.
12	1	.204	7.39	0
12	2	.207	7.36	-.03
12	3	.202	7.41	+.02
12	4	.209	7.34	-.05

Other fuels were checked in a similar manner. It can be seen that the reproducibility of estimating the incipient detonation point was consistent within a maximum of plus or minus .05 units. It must be pointed out, however, that a different operator could easily get consistent results of higher or lower readings than those mentioned above. Since the oscillograph method is the best procedure yet found for detecting incipient detonation in the judgment of the authors, the fallibility of this method had to be accepted.



comparative basis for several years is given below for evaluation of independent determination. The technique is rapid, accurate, a simple operation and compares well with the results now being actively in development on the millimeter wave active radar. The active radar is given below for comparison with the independent determination.

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Year	1960	1961	1962	1963	1964
1960	100.0	100.0	100.0	100.0	100.0
1961	100.0	100.0	100.0	100.0	100.0
1962	100.0	100.0	100.0	100.0	100.0
1963	100.0	100.0	100.0	100.0	100.0
1964	100.0	100.0	100.0	100.0	100.0

of the nature, the possibility of this action can be  
 not found for restoring original condition in the judgment  
 shown. Hence the well-known method is the best procedure  
 possible in light of lower conditions than these conditions  
 with, that a different procedure could easily be considered  
 at this or about. On some. It must be further said, how-  
 ever, that the possibility of this action can be

## Education

## ENGINE INDICATOR

No error was assumed for the M.I.T. high-speed engine indicator card machine as the cyclic variation of cylinder pressures caused a line width and scatter of points greater than any inherent error in the machine.

Pressure measurement readings taken at  $110^{\circ}$  B.T.C. and  $140^{\circ}$  A.T.C. (for equivalent cycle computation) were accurate to the width of the compression and expansion lines at these points giving accuracy of within 1%. The measurement of peak pressures was more difficult due to considerable cyclic variation during the combustion process causing a spread of as much as 5% in peak pressure points. The actual average could be plus or minus 2% from the average measured.

The balanced pressure pick-up unit used was tested and the actuating pressure difference required was found to be  $.37 \text{ lb/in.}^2$ . Assuming the unit acted the same under operating conditions, this would be a 1.5 - 2.0% error at  $110^{\circ}$  B.T.C. and negligible error at all other pressures measured.

## CLEARANCE VOLUME

The clearance volume of the engine was carefully measured by checking the measured clearance volume against figures obtained by Professor W. Leary, of the actual compression ratios required for definite cylinder volumes. The piston was set on top-dead-center, both valves closed

The first was prepared for the 1914-1915 season  
indicating the results of the 1914-1915 season in general  
and showing a list of the names of the persons who  
were the largest contributors to the fund.

The second was prepared for the 1915-1916 season  
and the 1916-1917 season, showing the results of the  
1915-1916 season in general and the results of the  
1916-1917 season in general, and showing a list of the  
names of the persons who were the largest contributors  
to the fund. The third was prepared for the 1917-1918  
season, showing the results of the 1917-1918 season in  
general, and showing a list of the names of the persons  
who were the largest contributors to the fund.

The fourth was prepared for the 1918-1919 season,  
showing the results of the 1918-1919 season in general,  
and showing a list of the names of the persons who were  
the largest contributors to the fund. The fifth was  
prepared for the 1919-1920 season, showing the results  
of the 1919-1920 season in general, and showing a list  
of the names of the persons who were the largest  
contributors to the fund.

The sixth was prepared for the 1920-1921 season,  
showing the results of the 1920-1921 season in general,  
and showing a list of the names of the persons who were  
the largest contributors to the fund. The seventh was  
prepared for the 1921-1922 season, showing the results  
of the 1921-1922 season in general, and showing a list  
of the names of the persons who were the largest  
contributors to the fund.



and distilled water was poured into the clearance volume until the volume was filled. The volume of water used was checked against the figures mentioned above. Reproducibility was found to be within 2%. It is estimated that less than 1% error in clearance volume versus compression ratio existed during the experiment.

#### AIR MEASUREMENT

Mass rate of air flow was calculated by the expression  $M_a = .1825 (hP_o/T_o)^{\frac{1}{2}}$  where  $M_a$  = lb. air/sec.,  $h$  = pressure drop across the orifice in inches of water,  $P_o$  = pressure before the orifice in inches of mercury and  $T_o$  = temperature of air before the orifice in °F abs.

Air flow was one of the most difficult of the variables to measure due to a periodic surge in the pressure drop across the orifice. A surge occurred when the main air supply compressor turned on causing a small increase in  $P_o$  and a larger increase in pressure drop across the orifice, despite two pressure regulator valves in series between the supply line and the engine induction system. Since the averaging of the value of pressure drop was done by the same operator for all runs, it is felt that the relative values of  $M_a$  are quite good, and, since the surges were on the order of 5%, the absolute error should not exceed 2%.

#### FUEL MEASUREMENT

The rotometer was calibrated by weighing each fuel with a sensitive balance. This calibration was done at various



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Basic values for  $\alpha$  and  $\beta$  are 0.05 and 0.01, respectively, and  $\beta$  is

— 422 — *Journal of the American Medical Association*, Chicago, Ill., February 22, 1936

Radl, J. and others 1991, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 2679,

TABLE 1. *Summary of the results of the 1990-1991 survey of the distribution of the 10 most common species of fish in the Great Lakes*

1. The first group of authors (e.g., [1, 2]) considers the problem of the control of the motion of a mechanical system with a variable structure. The control is assumed to be piecewise constant in time. The control is determined by the solution of a problem of the control of a mechanical system with a fixed structure. The control is determined by the solution of a problem of the control of a mechanical system with a fixed structure. The control is determined by the solution of a problem of the control of a mechanical system with a fixed structure.

polymers with a molecular weight of 100,000 and a polydispersity of 1.05.

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Figure 1. A typical 1000 Hz tone with 1000 samples.

[illegible]

There are also factors the authors do not

estimating will be a lot easier than it will be for you and me.

and results: all of these studies have shown that the use of

\*In place of each termite mound I collected all termites

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and the other two are the same as the previous ones.

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...and the ...

The author of 8, the evangelist, was clearly not aware of

The following are the results of the analysis:

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fuel temperatures, the range being approximately 15°F.

The curves could be read with a temperature accuracy of plus or minus 1° F. During running, however, the rotameter reading had an estimated variation of plus or minus 2%.

#### INLET TEMPERATURE

The inlet temperature was controlled within plus or minus 1°F of the desired reading.

#### RPM

The RPM could be controlled within a negligible error.

#### EXHAUST PRESSURE

The exhaust pressure was held within a plus or minus .5 psi when operating with high exhaust pressure. When low exhaust pressure was used, the variation was less than .1 inch of mercury.

that temperature, the water being approximately 15°C.

The water could be kept at a constant temperature of 15°C or 20°C. In fact, however, the temperature of the water varied by about 1°C.

These results

are listed in Table I and are plotted in Figure 1.

Figure 1 is a plot of the rate of reaction

and

the rate of reaction is plotted in Figure 2.

Figure 2 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 3.

Figure 3 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 4.

Figure 4 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 5.

Figure 5 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 6.

Figure 6 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 7.

Figure 7 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 8.

Figure 8 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 9.

Figure 9 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 10.

Figure 10 is a plot of the rate of reaction

and the rate of reaction is plotted in Figure 11.

# REPRODUCIBILITY OF RESULTS

The criteria selected for the reproducibility of the apparatus were the pressure and specific volume at 110° B.T.C.

The recording run variables (i. e. inlet temperature, RPM, spark advance, coolant temperature, rotameter reading, exhaust pressure, inlet pressure) were duplicated correcting for fuel temperature. Incipient detonation was then, in the judgment of the oscillograph operator, reproduced. The reproducibility of critical experimental values is tabulated below for comparison.

<u>Triptane</u>	Compression Ratio	f	Critical Pressure	At 110° B.T.C. Vol.	Pressure
Recording run	7.80	.037	890	11.39	24.7
Check run	7.84	.037	890	11.30	24.7
<u>Iso-Octane</u>					
Recording run	8.76	.1025	723	14.4	20.9
Check run	8.67	.104	725	14.38	20.9
<u>Di-iso-butylene</u>					
Recording run	6.82	.051	705	12.97	21.5
Check run	6.77	.0518	708	12.8	21.5

A check run was not attempted on Ethyl Benzene due to lack of time.

It can be seen from the above data that the compression ratio variation at the maximum was 1%. The maximum variation





in residual gas concentration was about 2%. Critical pressure and the specific volume and pressure at 110° B.T.C. were matched with negligible error. It is, therefore, estimated that the overall reproducibility of the apparatus was within plus or minus 1%.

It is noted that the Commission was not able to  
obtain the necessary information and that the  
results were not satisfactory. It is, there-  
fore, recommended that the Commission be  
authorized to obtain the necessary information  
and that the results be reported to the  
Commission.

Name		Address		City		State		Country	
John Doe		123 Main St.		New York		New York		U.S.A.	
Jane Smith		456 Elm St.		Los Angeles		California		U.S.A.	
Robert Brown		789 Oak St.		Chicago		Illinois		U.S.A.	
Mary White		101 Pine St.		San Francisco		California		U.S.A.	
James Black		202 Cedar St.		Boston		Massachusetts		U.S.A.	
Elizabeth Green		303 Maple St.		Philadelphia		Pennsylvania		U.S.A.	
William Hall		404 Birch St.		Houston		Texas		U.S.A.	
Margaret King		505 Spruce St.		Portland		Maine		U.S.A.	
Charles Lee		606 Ash St.		Seattle		Washington		U.S.A.	
Dorothy Miller		707 Hickory St.		Denver		Colorado		U.S.A.	
Frank Wilson		808 Walnut St.		San Diego		California		U.S.A.	
Helen Young		909 Cherry St.		Austin		Texas		U.S.A.	
George Taylor		1010 Elm St.		Phoenix		Arizona		U.S.A.	
Betty Adams		1111 Oak St.		Dallas		Texas		U.S.A.	
Edward Baker		1212 Pine St.		San Jose		California		U.S.A.	
Frances Clark		1313 Cedar St.		San Antonio		Texas		U.S.A.	
Harold Evans		1414 Maple St.		Fort Worth		Texas		U.S.A.	
Irene Foster		1515 Birch St.		Jacksonville		Florida		U.S.A.	
Jack Gibson		1616 Spruce St.		Nashville		Tennessee		U.S.A.	
Katherine Hall		1717 Ash St.		Memphis		Tennessee		U.S.A.	
Leo Hill		1818 Hickory St.		Little Rock		Arkansas		U.S.A.	
Mildred Jones		1919 Walnut St.		Birmingham		Alabama		U.S.A.	
Norman King		2020 Cherry St.		Mobile		Alabama		U.S.A.	
Olivia Lee		2121 Elm St.		Tulsa		Oklahoma		U.S.A.	
Paul Miller		2222 Oak St.		Oklahoma City		Oklahoma		U.S.A.	
Rebecca Smith		2323 Pine St.		Lawton		Oklahoma		U.S.A.	
Samuel Taylor		2424 Cedar St.		Muskogee		Oklahoma		U.S.A.	
Theresa White		2525 Maple St.		Ada		Oklahoma		U.S.A.	
Victor Black		2626 Birch St.		Bartlesville		Oklahoma		U.S.A.	
Wendy Green		2727 Spruce St.		Claremore		Oklahoma		U.S.A.	
Xavier Hall		2828 Ash St.		Cottontown		Oklahoma		U.S.A.	
Yvonne King		2929 Hickory St.		Duncan		Oklahoma		U.S.A.	
Zoe Lee		3030 Walnut St.		Edmond		Oklahoma		U.S.A.	

It is recommended that the Commission be  
authorized to obtain the necessary information  
and that the results be reported to the  
Commission.

## SUGGESTIONS FOR FUTURE STUDY

Since the effect of residual gas concentration on the pressure-time characteristics of the fuels studied was not found to be the cause of the observed RPM-detonation reversal, it is suggested:

1. A similar experiment be conducted with no residual gas per cycle to see if the reversal effect is still present.
2. The straight line variation of critical pressure with residual gas concentration, as was assumed, should be investigated.
3. The effect of radiation from the flame front to the end gas should be studied.
4. The effect of inhibiting reactions (if any) in the early part of the compression process should be further investigated.





## APPENDIX A

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## THE EQUIVALENT CYCLE METHOD

Symbols:

$B$  = lbs. of air used per cycle

$f$  = ratio of mass of residual gas to total gas mass per cycle

$F$  = ratio of mass of fuel to mass of air per cycle

$M$  = total gas mass

$V$  = total gas volume

### Derivation

In the cylinder:

The mass of fuel and air used per cycle =  $B(1 + F)$  lbs.

Then the total gas mass per cycle =  $\frac{B(1 + F)}{(1 - f)}$  lbs.

In the Hershey, Eberhardt, and Hottel charts of the thermodynamic characteristics of fuel-air mixtures before and after combustion:

The total chart mass =  $(1 + F)$  lbs.

$$\begin{aligned}\text{Therefore } \frac{V_{\text{chart}}}{V_{\text{cyl}}} &= \frac{M_{\text{chart}}}{M_{\text{cyl}}} = \frac{(1 + F)}{B(1 + F)/(1 - f)} \\ &= \frac{(1 - f)}{B}\end{aligned}$$

$$\text{And thus, } V_{\text{chart}} = V_{\text{cyl}} \frac{(1 - f)}{B}$$



1911

Let  $x$  be the number of...

Let  $y$  be the number of...

Let  $z$  be the number of...

Let  $w$  be the number of...

Let  $v$  be the number of...

Let  $u$  be the number of...

Let  $t$  be the number of...

Let  $s$  be the number of...

$$\text{Let } \frac{(x+y+z)}{(x+y+z)} = \frac{(x+y+z)}{(x+y+z)}$$

Let  $r$  be the number of...

Let  $q$  be the number of...

Let  $p$  be the number of...

Let  $o$  be the number of...

$$\text{Let } \frac{(x+y+z)}{(x+y+z)} = \frac{(x+y+z)}{(x+y+z)}$$

$$\frac{(x+y+z)}{(x+y+z)} = \frac{(x+y+z)}{(x+y+z)}$$

$$\frac{(x+y+z)}{(x+y+z)} = \frac{(x+y+z)}{(x+y+z)}$$

SAMPLE CALCULATION FOR  
ISO-OCTANE AT 900 RPM  
(RUNS NO. 13 and 14)

Given:  $P_1 = 31.68'' \text{ Hg}$   $M_a = .00874 \text{ lb/sec.}$   
 $T_1 = 120^\circ \text{ F}$   $F = 117.6\% \text{ chem. correct}$   
 $P_e = 45 \text{ psia}$   $M_f = .000675 \text{ lb/sec.}$   
 $r = 8.72$

Required to find (f):

$$V_{\text{clearance}} = .002798 \text{ ft.}^3$$

$$V_{\text{displaced}} = .01958 \text{ ft.}^3 \quad \text{at } 140^\circ \text{ A.T.C.}$$

$$V_{\text{cylinder}} = .022378 \text{ ft.}^3$$

$$B = \frac{.00874 \times 2 \times 60}{900} = .001164 \text{ lb/air cycle}$$

Now for first approximation assume  $f = .102$

$$\text{Then } V_{\text{chart}} = .022378 \times \frac{(1 - .102)}{.001164} = 17.23 \text{ ft.}^3/\text{lb.}$$

At  $140^\circ \text{ A.T.C.}$   $P = 56.95 \text{ psia}$  from indicator card

Now locating this point on the "burned" thermodynamic charts and expanding isentropically to an exhaust pressure of 45 psia, a corresponding volume was read which was 20.8 ft.<sup>3</sup>/lb.

$$V_{\text{chart}} = .002798 \times \frac{(1 - .102)}{.001164} = 2.155 \text{ ft.}^3/\text{lb. at top center}$$

$$\text{And, therefore, } f = \frac{2.155}{20.8} = .1036$$

Required to find thermodynamic conditions at  $110^\circ \text{ B.T.C.}$ :

$$V_{\text{clearance}} = .002798$$

$$V_{\text{displaced}} = .01557 \quad \text{at } 110^\circ \text{ B.T.C.}$$

$$V_{\text{cylinder}} = .018368 \text{ ft.}^3$$



$$V_{\text{chart}} = .018368 \times \frac{(1 - .1036)}{.001164} = 14.12 \text{ at } 110^{\circ} \text{ B.T.C.}$$

From indicator card  $P = 20.85 \text{ psia}$

In the second run, exhaust pressure was lowered to  $14.7 \text{ psia}$ .

To obtain similar thermodynamic conditions at  $110^{\circ} \text{ B.T.C.}$ ,

it was necessary to use:

$$P_1 = 32.66 \text{ "Hg}$$

$$T_1 = 224^{\circ} \text{ F}$$

$$M_a = .009625 \text{ lb/sec.}$$

$$M_f = .000751 \text{ lb/sec.}$$

This resulted in a critical compression ratio of 6.93.

$$V_{\text{clearance}} = .003643 \text{ ft.}^3$$

$$V_{\text{displaced}} = .01958 \text{ ft.}^3 \text{ at } 140^{\circ} \text{ A.T.C.}$$

$$V_{\text{cylinder}} = .023223 \text{ ft.}^3$$

$$B = \frac{.009625 \times 2 \times 60}{900} = .001282 \text{ lb/air cycle}$$

For first approximation assume  $f = .05$

$$\text{Then } V_{\text{chart}} = .02322 \times \frac{(1 - .05)}{.001282} = 17.2 \text{ ft.}^3/\text{lb. at } 140^{\circ} \text{ A.T.C.}$$

From indicator card  $P = 59.45 \text{ psia}$

Again expanding isentropically from this point on the

"burned" chart, but to an exhaust pressure of  $14.7 \text{ psia}$ ,

the corresponding volume was  $51.0 \text{ ft.}^3/\text{lb.}$

$$V_{\text{chart}} = .003644 \times \frac{(1 - .05)}{.001282} = 2.70 \text{ ft.}^3/\text{lb. at top center}$$

$$\text{And } f = \frac{2.70}{51.0} = .0529$$



$$T_{\text{dew}} = 14.18 \text{ at } 100 \text{ hPa}$$

$$\text{from } T_{\text{dew}} = 14.18 \text{ hPa}$$

In the second run, the dew point was lowered to 14.7 hPa.

Of course, under atmospheric conditions at 100 hPa.

It was necessary to use:

$$T_1 = 20.14 \text{ hPa}$$

$$T_2 = 20.14 \text{ hPa}$$

$$T_3 = 20.14 \text{ hPa}$$

$$T_4 = 20.14 \text{ hPa}$$

This resulted in a critical compression ratio of 4.33.

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

Again, the dew point was lowered to 14.7 hPa.

Of course, under atmospheric conditions at 100 hPa.

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

$$T_{\text{dew}} = 20.14 \text{ hPa}$$

To find the thermodynamic conditions at 110° B. T. C.:

$$V_{\text{clearance}} = .0036437 \text{ ft.}^3$$

$$V_{\text{displaced}} = .01557 \text{ ft.}^3$$

$$V_{\text{cylinder}} = .019213 \text{ ft.}^3$$

$$V_{\text{chart}} = .019213 \frac{(1 - .0529)}{.001282} = 14.21 \text{ ft.}^3/\text{lb. at } 110^\circ \text{ B.T.C.}$$

From indicator card  $P = 20.85$  psia.

The points thus found for 110° B.T.C. were indistinguishable from each other when plotted on the "unburned" chart, and, therefore, were considered to be identical in entropy.



## APPENDIX B



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1954

CATHODE RAY  
OSCILLOGRAPH

FUEL  
SUPPLY

EXHAUST  
PRESSURE  
MANOMETER

ROTAMETER

ORIFICE  
PRESSURE  
MANOMETER

FUEL PUMP

DRYING  
TOWER

EXHAUST  
PRESSURE  
VALVE

ELECTRIC  
HEATER

MIXING  
TANK

THROTTLE  
VALVE

SURGE  
TANK

SUPER-  
CHARGER  
PRESSURE  
VALVE

FLOW-RATE  
MANOMETER

HIGH-SPEED  
INDICATOR

STROBOTAC

DYNAMO-  
METER

C.F.R.  
ENGINE

STEAM  
WATER

1. INDICATOR PICKUP
2. RATE OF PRESSURE PICKUP
3. SPARK PLUG

FIGURE 1  
OVERALL LAY-OUT  
of  
EXPERIMENTAL C.F.R.  
SET-UP



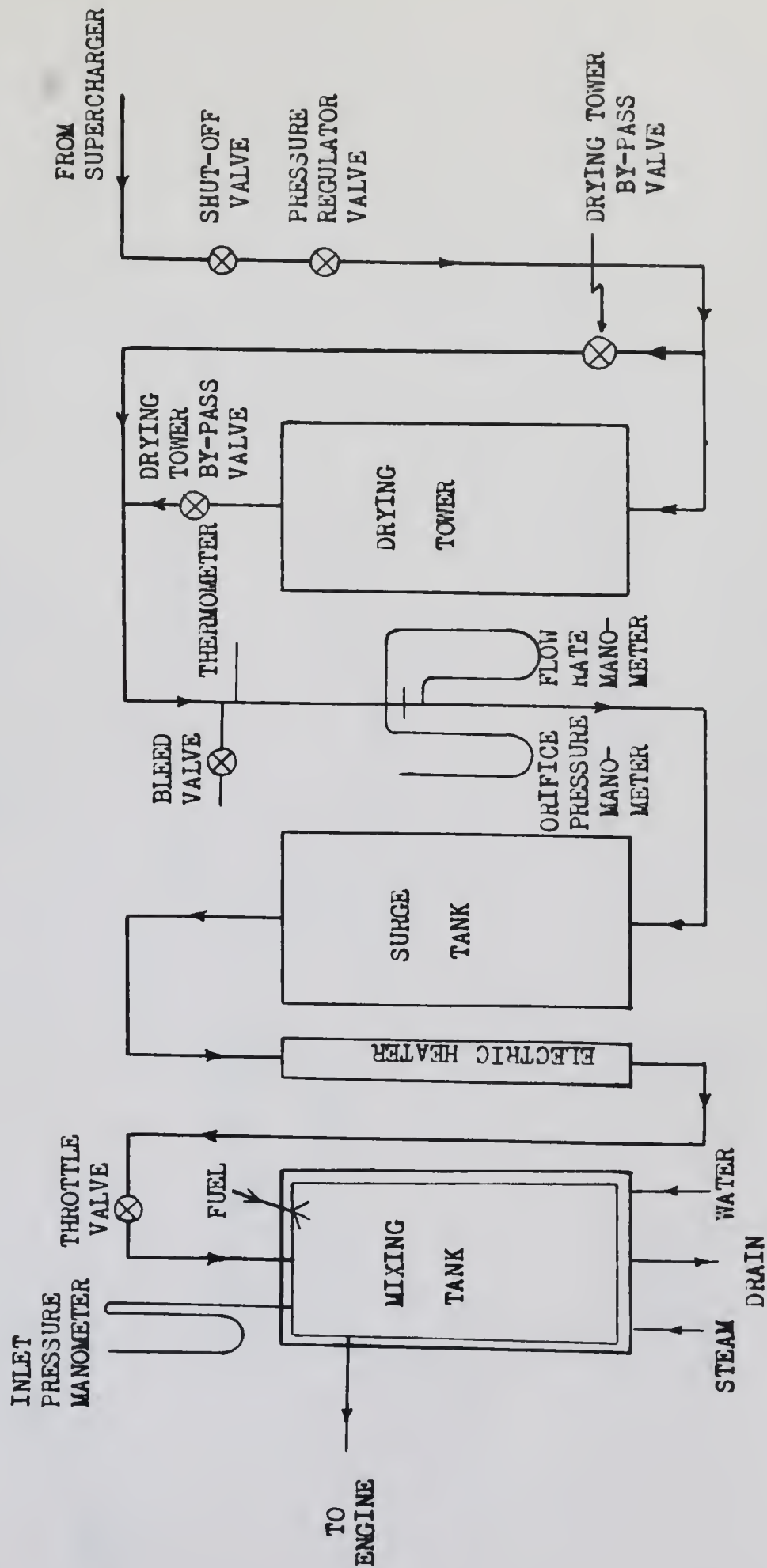


FIGURE 2  
DETAILED LAY-OUT  
of  
INDUCTION SYSTEM





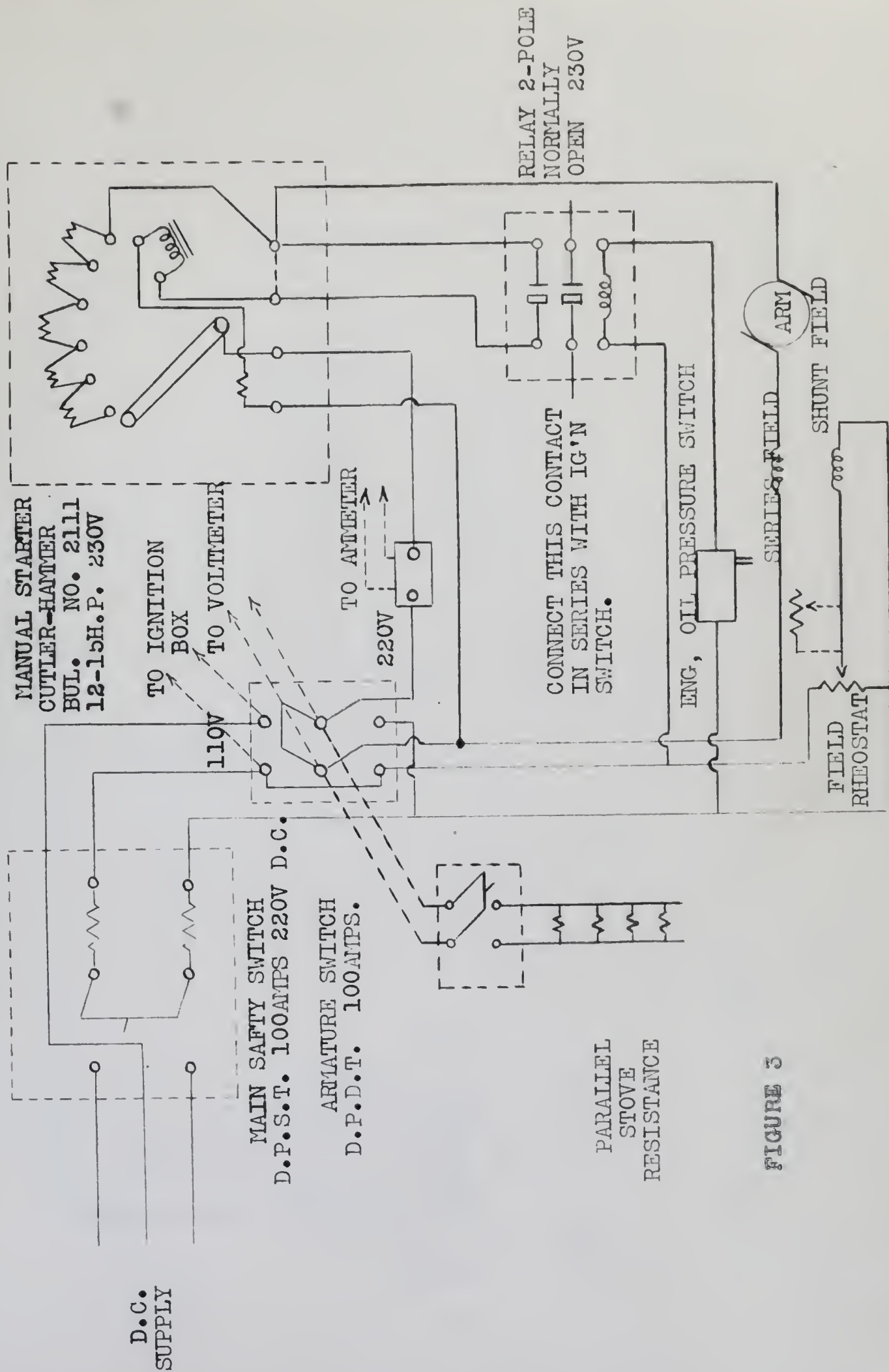


FIGURE 3



# HIGH SPEED INDICATOR

M. I. T.

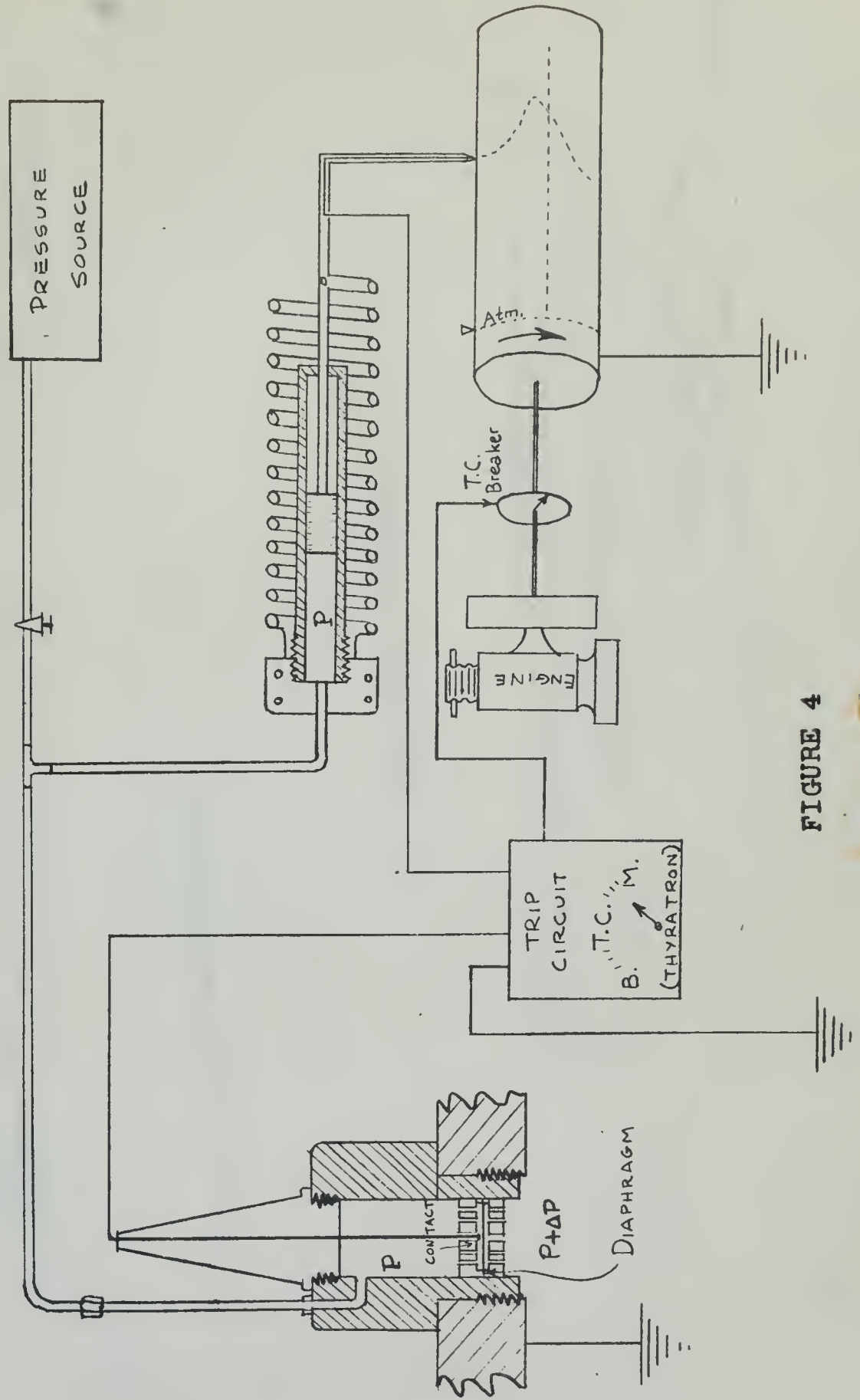


FIGURE 4







May 12, 1947

FIGURE NO. 5

Triptane, 900 R.P.M.

Triptane, 1800 R.P.M.

Ethyl Benzene, 900 R.P.M.

S.R.10, 900 R.P.M.

Iso-Octane, 1800 R.P.M.

Iso-Octane, 900 R.P.M.

Ethyl Benzene, 1800 R.P.M.

S.R.10, 1800 R.P.M.

RESIDUAL GAS CONCENTRATION (%)

SLOAN AUTOMOTIVE LABORATORY

CRITICAL PRESSURE in LBS. per sq. IN.

.11

.10

.09

.08

.07

.06

.05

.04

.03

1000

900

800

700

600

500





PLOTS OF  
 CYLINDER PRESSURE  
 vs.  
 TIME  
 FOR ISO-OCTANE

Sloan Laboratory  
 May 13, 1947

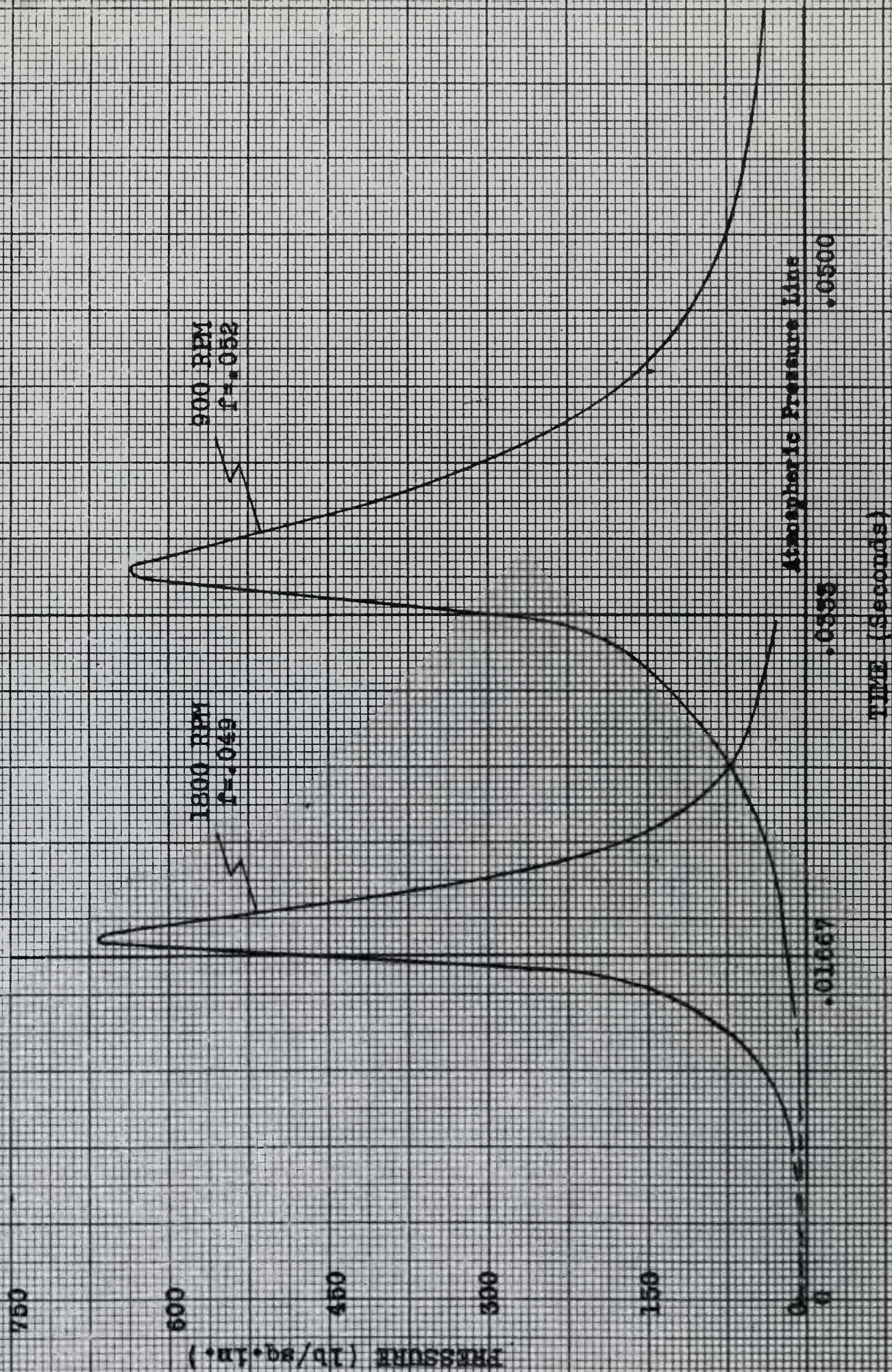


Fig. 6





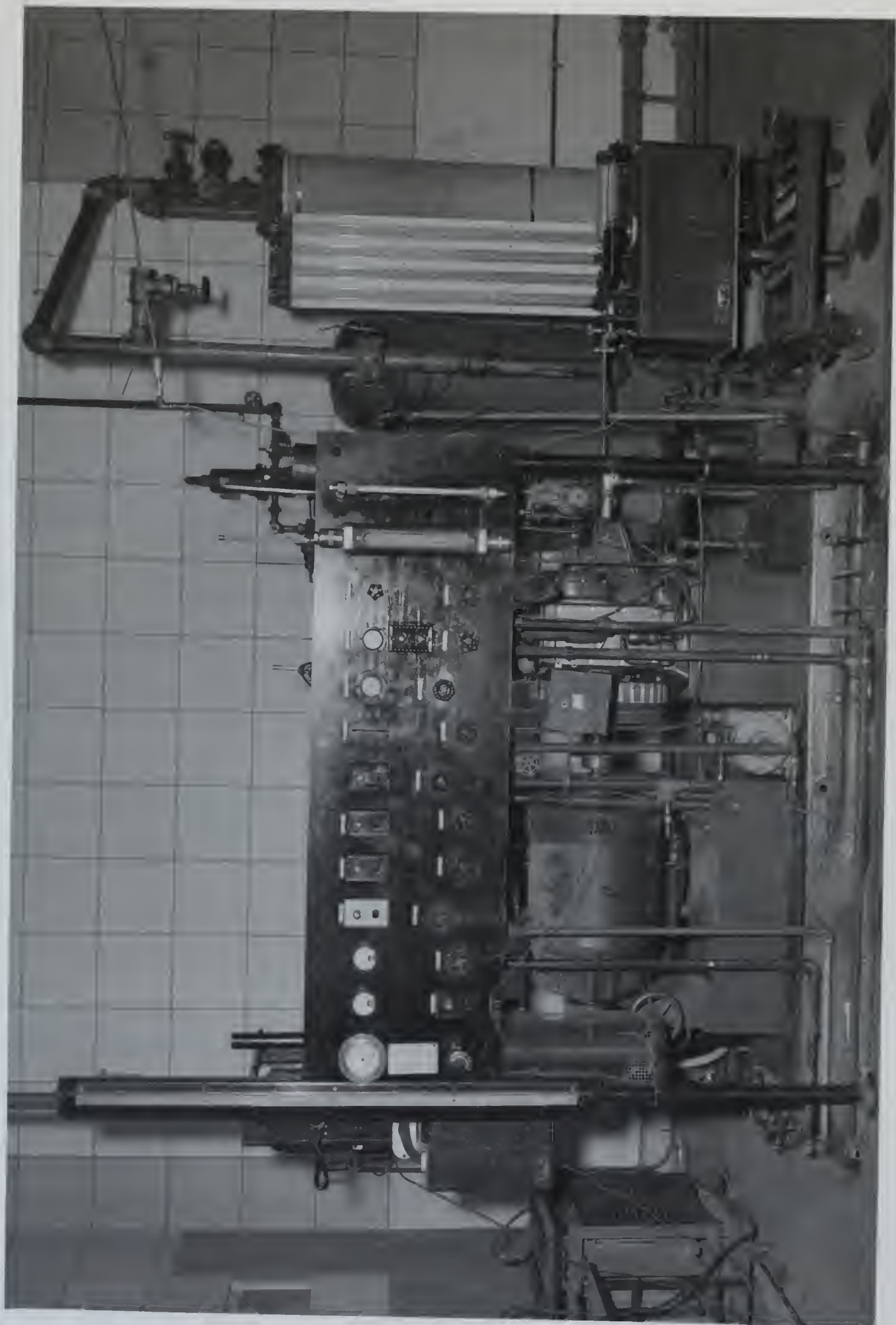
## M.I.T. AERO ENGINE LABORATORY

CFR ENGINE

3.25 BORE	4.5 STROKE	Variable	COMPRESSION RATIO
-----------	------------	----------	-------------------

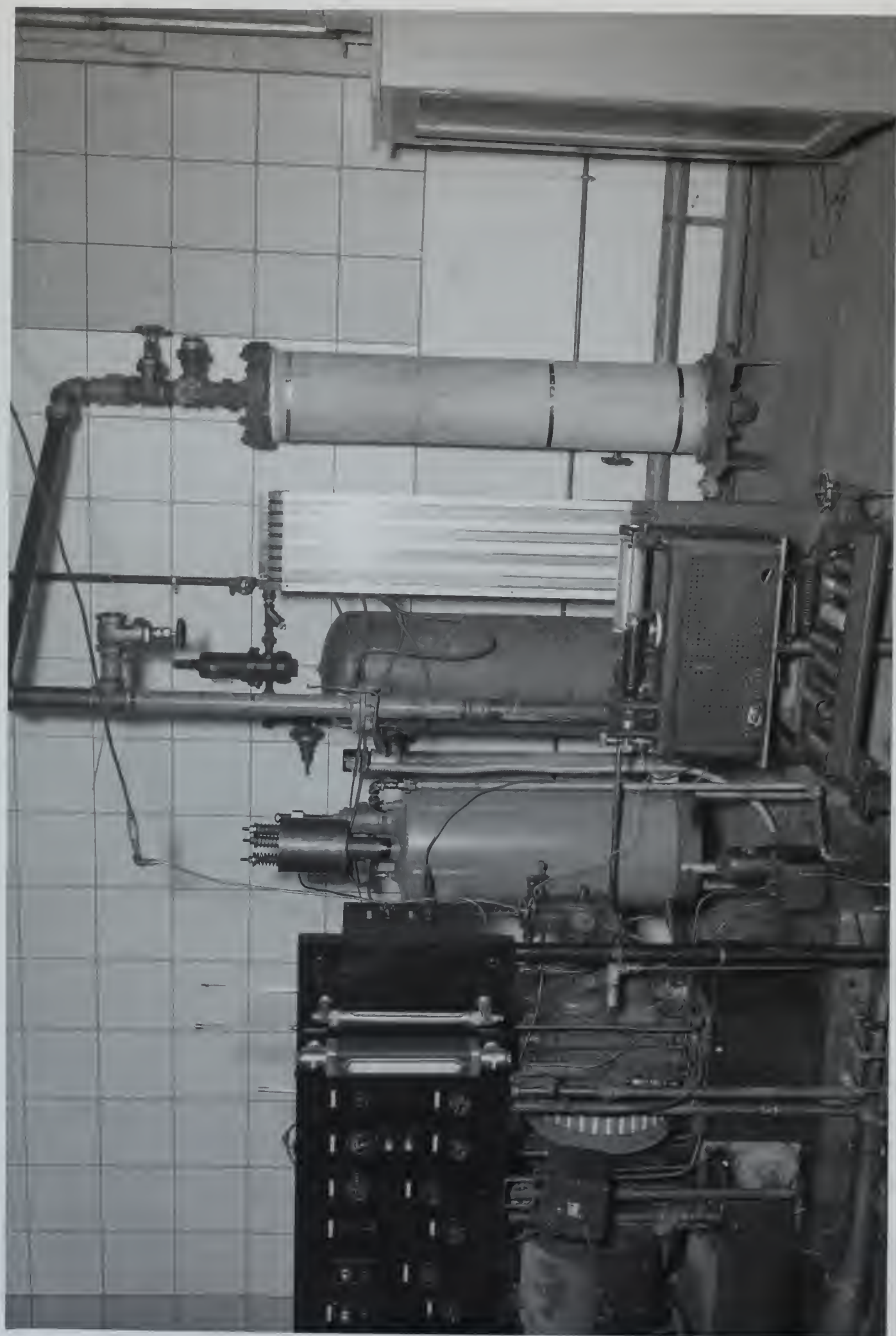
REMARKS	DRIE	TIME	RUN	P <sub>a</sub>	P <sub>e</sub>	P <sub>i</sub>	P <sub>o</sub>	T <sub>a</sub>	T <sub>i</sub>	T <sub>f</sub>	M <sub>a</sub>	F	M <sub>f</sub> 10 <sup>3</sup>	Roto	r <sub>min</sub>	r	SA	N	P <sub>ent</sub>	f	V	P	
				"Hg	P <sub>ma</sub>	"Hg	"Hg	°F	°F	°F	lb/sec		lb/sec					°BIC	RPM	P <sub>ma</sub>		ft <sup>3</sup> /lb	P <sub>ma</sub>
TRIPTANE	4-17		1	29.79	45	43.94	44.64	91	120	87	.01307	.01775	1018	8.8	.066	8.95	15	400	1023	.0755	9.7	28.0	
	4-19		2	30.08	45	43.98	44.98	100	160	88	.01391	.01775	1086	9.15	.112	7.70	15	900	1005	.036	9.73	28.0	
	4-18		3	29.91	45	40.21	42.26	82	120	84	.02222	.01775	173	12.93	.048	9.21	20	1800	920	.077	11.35	24.8	
	4-17		4	29.83	45	40.95	43.44	100	200	88	.0238	.01775	1852	13.52	.142	7.80	20	1800	890	.037	11.34	24.1	
Check of run #4	4-18		5	29.80	45	40.93	43.44	100	200	88	.0238	.01775	1852	13.52	.158	7.84	20	1800	895	.037	11.3	24.7	
ETHYL BENZENE	4-29		6	30.20	45	33.45	34.47	80	150	87	.00935	.0865	0808	8.02	.098	8.53	20	400	820	.0988	13.33	22.78	
	4-29		7	30.20	45	33.45	34.47	80	150	87	.00935	.0865	0808	8.02	.140	8.03	20	900	775	.0549	13.33	22.75	
	5-1		8	29.95	45	32.7	34.2	80	150	85	.01652	.0865	1428	11.1	.179	7.63	25	1800	635	.118	15.15	21.4	
	5-1		9	29.95	45	33.15	35.1	94	235	90	.0178	.0865	1590	12.35	.246	6.87	25	1800	613	.0729	15.09	21.4	
ISO-OCTANE	4-24		10	29.95	45	32.39	33.35	76	120	85	.07113	.0782	1390	10.22	.080	8.76	25	1800	723	.1025	14.0	20.9	
check of run #10	4-24		11	30.46	45	32.34	33.94	86	120	86	.072	.0782	1390	10.2	.087	8.67	25	1800	725	.104	14.38	20.9	
	4-24		12	29.85	45	33.50	35.60	95	249	94	.085	.0782	1450	11.00	.204	7.39	25	1800	685	.0889	14.59	20.9	
	4-24		13	29.81	45	32.66	33.36	98	229	90	.08463	.0782	0751	7.1	.259	6.43	20	400	650	.0529	14.21	20.85	
	4-24		14	29.81	45	31.68	32.06	98	120	90	.08814	.0782	0675	6.85	.083	8.72	20	400	645	.1036	14.12	20.85	
SR-10	4-15		15	29.95	45	30.65	32.05	92	120	90	.0160	.08	1280	9.98	.140	8.03	25	1800	610	.118	15.90	19.0	
	4-15		16	29.95	45	31.85	33.80	103	210	93	.01783	.08	1430	10.7	.312	6.59	25	1800	580	.0545	15.84	18.0	
	4-15		17	30.00	45	33.15	34.35	80	120	88	.00944	.08	0713	7.3	.190	8.03	20	400	730	.1053	13.09	24.5	
	4-15		18	30.00	45	34.4	35.15	86	195	91	.0106	.08	0894	7.6	.273	6.82	20	400	705	.051	12.97	21.5	
check of run #18	4-15		19	30.00	45	34.4	35.15	79	145	83	.0109	.08	0870	7.6	.280	6.77	20	400	700	.0518	12.8	21.5	



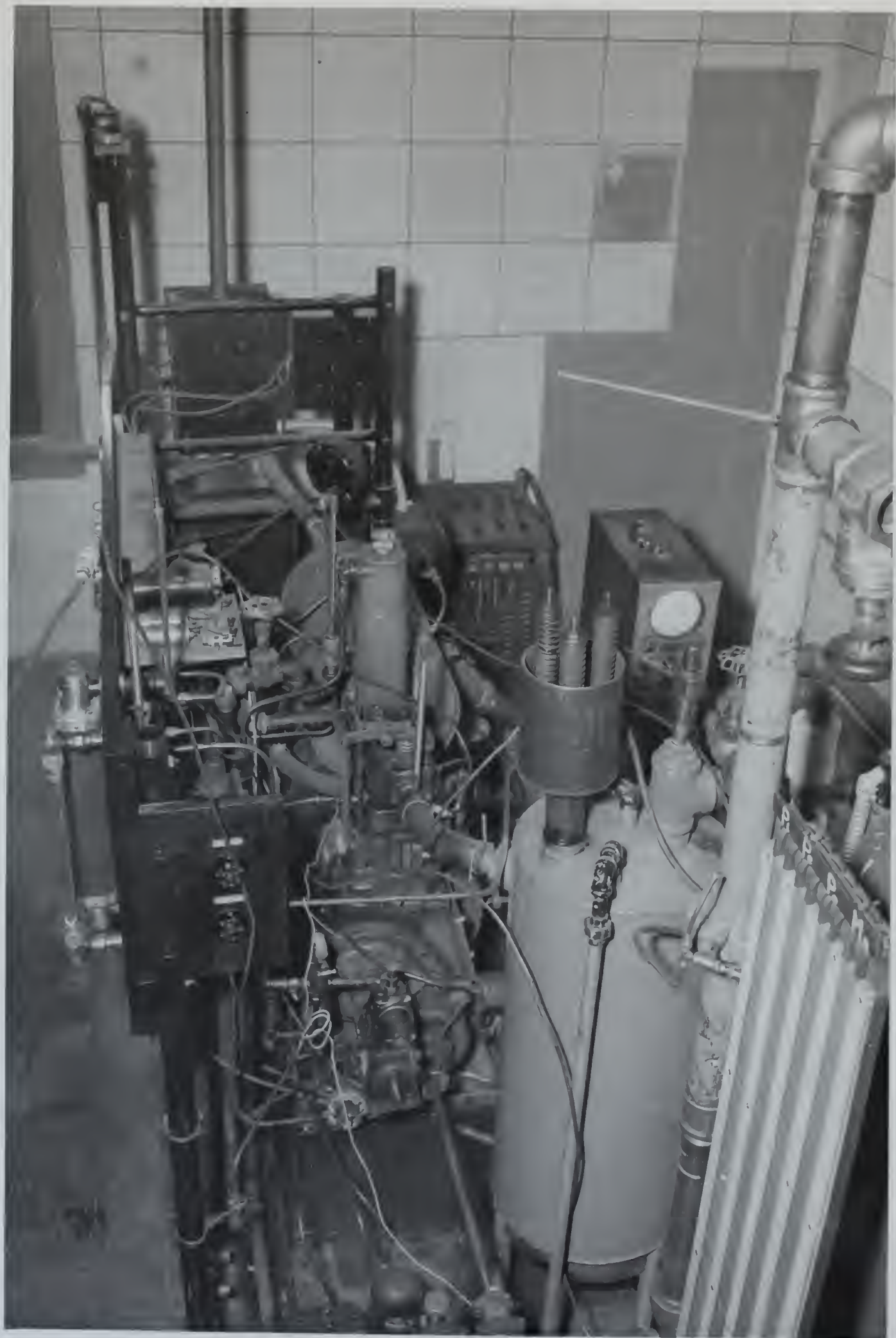






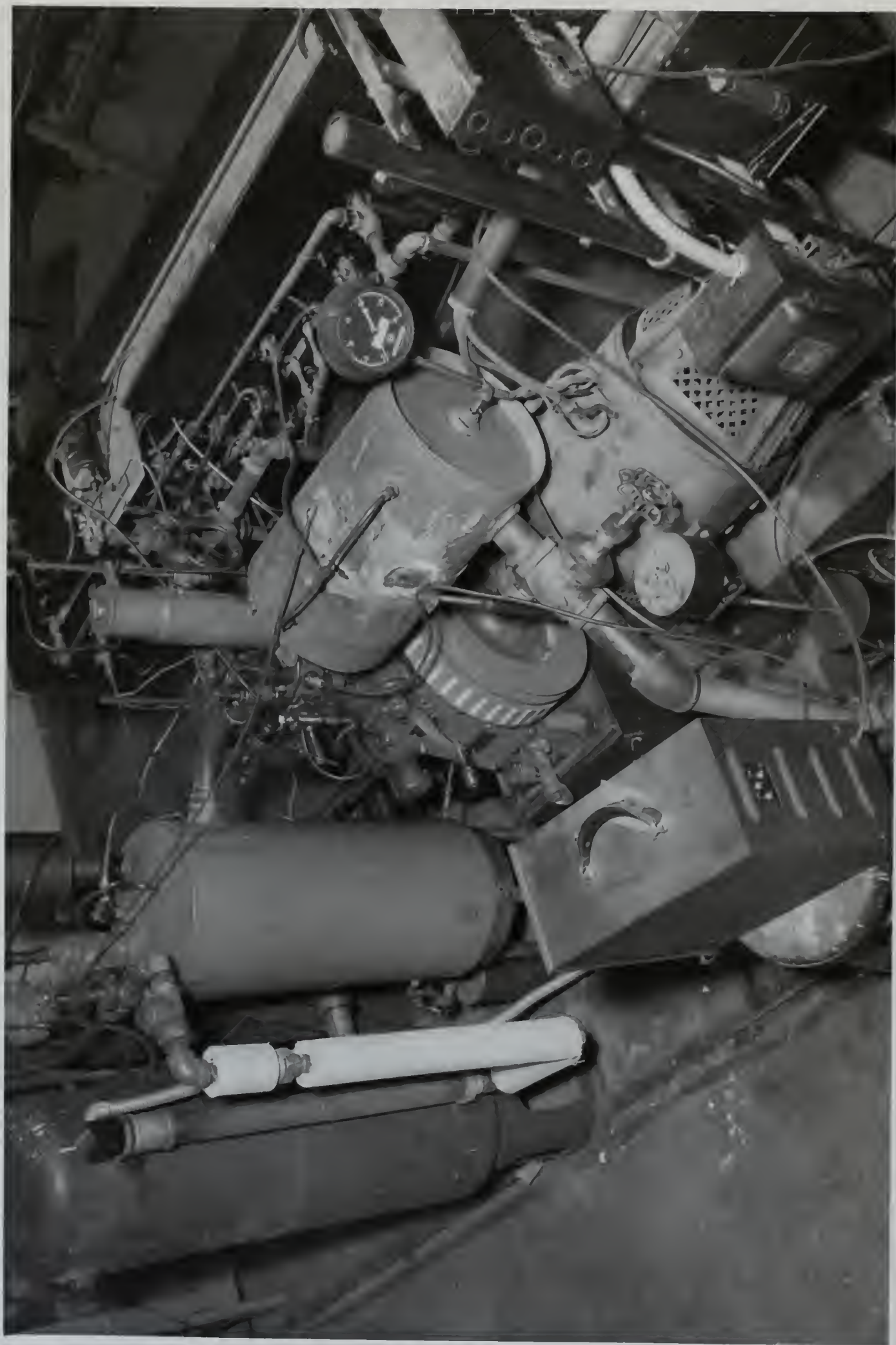














## APPENDIX C



APPENDIX 2

#### REFERENCES

- (1) Leary, W. A., and Taylor, E. S., The Significance of the Time Concept in Engine Detonation, N.A.C.A. ARR, January 1943.
- (2) Taylor, E. S., and Draper, C. S., "A New High Speed Engine Indicator", Mechanical Engineering, Vol. 55, No. 3, 1933, p. 169.
- (3) Draper, C. S., "Pressure Waves Accompanying Detonation in the Internal Combustion Engine", JAS, Vol. 5, No. 6, April 1938.
- (4) Taylor, E. S., Leary, W. A., and Diver, J. R., Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation, N.A.C.A. Report No. 699.

1. The first part of the document is a letter from the President of the United States to the Congress, dated January 3, 1862. It is a copy of the original letter, and is signed by Abraham Lincoln. The letter is addressed to the Senate and the House of Representatives, and is dated January 3, 1862. The letter is a copy of the original letter, and is signed by Abraham Lincoln. The letter is addressed to the Senate and the House of Representatives, and is dated January 3, 1862.

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